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ESTIMATION OF TEMPORAL VARIATION RESILIENCE IN COTTON VARIETIES USING STATISTICAL MODELS

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Suitable cotton variety selection is imperative to cope with temporal variations for yield enhancement and sustainability under unpredictable climatic conditions. Cotton varieties including transgenic (*Bacillus thuringiensis*) and non-transgenic (non Bt.) were sown from 10-March to 21-June with 20 days interval for two growing seasons (2012 and 2013) consecutively while cotton sowing after wheat harvest is normal practice at farmers' field in Cotton-Wheat cropping system of Punjab-Pakistan. Phenology, growth indices, seed cotton yield (SCY) and its heat use efficiency of varieties were estimated on daily basis by using statistical models. Seed cotton yield (SCY) was significantly correlated with crop duration exhibiting delays in planting (21-June) impact on shortening of phenophases i.e. first square, flower, boll initiation and boll opening by 8, 7, 4 and 6 days, respectively compared with 10-May planting in first season while second season advanced 0-3 days owing to deviation in frequency of cold shock <11 °C and heat stress >35 °C. Long crop cycle varieties AA-802 and IR-3701 took 6-9 days more compared to short season NIAB-112. More heat units accretion 46, 33, 20 and 13 % to switch into next phenophase (first square, flower, boll initiation and boll opening) was computed in 10-May planting than 10-March due to excessive heat stress (>40 °C) during early phenophases while reduced variations observed in later phases. Reproductive stage initiation and accumulated higher thermal time delayed in late mature varieties compared to short one with lower root mean square error (RMSE) and higher coefficient of determination (R^2). Significant reduction in days after planting to attain maximum LAI, CGR, TDM and SCY-heat use efficiency (HUE_{SCY}) decreased with delay in planting with good statistical indices. Less impact of cold shock and heat stress on 21-April and 10-May plantings noted while 10-March and 21-June planting had higher incidence during early growth phases. Cotton varieties MNH-886 and NIAB-9811 (NIAB-Kiran) planted 30-March to 10-May exhibited higher resilience to variable weather conditions with fostered growth potential and yield. Variety NIAB-112 seemed heat tolerant and it can be recommend for early and especially for late plating while MNH-886 and NIAB-Kiran can be adopted at farmer's field in the region for maximizing cotton production under variable environment.
Keywords: Photo thermal, phenology, growth indices, heat stress, heat use efficiency, uncertain environment.

INTRODUCTION

Being the queen of fibers, cotton (*Gossypium hirsutum* L.) enjoys itself a predominant position amongst all other cash crops. It holds a lion's share in the foreign exchange (55%) of Pakistan and it production accounts for 1.5% in GDP and 7.1% in agriculture value addition (GOP, 2015). Invention of Bt. (*Bacillus thuringiensis*) genotypes has caused a hesitation among farmers whether to sow it or not owing to the controversial debates regarding it's sowing windows and some other complications. It is a well-known fact that crop growth, and development are weather dependent and it is considered as the most limiting factor in crop production (Hoogenboom, 2000; Yucel and Gormus, 2002; Hussain *et al*., 2015). Among environmental factors temperature affects cotton growth, developmental rate and yield. Temperature plays a crucial role as it determines the initiation and ending period of phenological stages during crop growing cycle (Luo, 2014). Cotton crop requires specific thermal time for the completion of each phenophase (Bange and Milroy, 2004; Khan *et al*., 2014) but critical phenophases are detrimentally affected by extremely high and cold temperature stresses. Although cotton is a perennial and morphologically indeterminate crop but it is phot period sensitive (Bange *et al.*, 2008). Degree day's accretion above an effective threshold temperature is considered as a good estimate for temperature impact on growth and development. Each phenological stage of varieties requires a specific thermal time for its initiation and completion but it is strongly influenced by sowing time (Sikder, 2009; Wajid *et al*., 2014). Sowing time and duration of growth cycle are determined by the daily temperature regulations. Therefore these regulations are defining climatic attributes for the ecological and regional optimum sowing time for sustainable yield potential (Bozbek *et al.,* 2006). Cotton sowing is also one of the most important critical aspects which leads to phenological development; conversion of assimilates and biomass to economic yield (Ali *et al.,* 2009). Early sowing (February and March) experiences cold temperature (<12 °C) stress which causes stand loss and delays in all developmental and phenological stages (Constable and Bange, 2006); poor biomass accumulation and ultimately lower seed cotton yield (Pettigrew 2008; Conaty *et al.,* 2012). Early post emergent plants exposed to cooler nights (<12 °C) called cold shock have to face cold stress and it slows down the developmental rates. Similarly if the night temperature is less than 20 °C then it hinders the boll development (Bange and Milroy, 2004). Overall these are reliable tools which are being used to evaluate the optimum sowing time for different cultivars (Bange *et al*., 2008; Sing *et al.,* 2007). Studies on the timings of phenological events, optimal conditions for each phenophase and connection with yield determinates are essential to boost up cotton productivity for suitable sowing time and cultivars under fluctuating environmental conditions. Planting of cotton at appropriate time provides maximum growing season which harvests peak solar radiation and accumulate more biomass (Arshad *et al*., 2007b) while delayed sowing exposed to sub optimal temperature at crop stand establishment stage and super optimal at reproductive stage (Akhter *et al.,*2002). Cotton-wheat cropping system is located in high temperature zone where summer day temperature exceeds 45 °C (heat stress >35 °C) which may adversely affect cotton growth and development and ultimately seed cotton yield (Rahman *et al.,* 2004). Physiological and metabolic processes of cotton have thermal range from 23-32 °C which is considered as optimal for growth and development (Pettigrew and Johnson, 2005; Conaty *et al.,* 2012). Late planting is usually resulted in yield reduction due to short reproductive phase as compared to early planting. Early sown cotton (April) produced more seed cotton yield due to higher boll retention while it could also reduce late season cold stress during reproductive phase by shifting it towards completion its life cycle earlier (Akhter *et al.,* 2002). The objective of optimum sowing time is to overcome the cold shock and to reduce heat stress incidence to ensure that fruit has sufficient time to mature with better quality and optimum seed cotton yield.

Heat tolerant genotypes are more productive than heat sensitive genotypes especially in the environments where heat stress occurs (Pettigrew, 2008) like the Cotton-Wheat cropping zone of Pakistan, has arid climatic conditions. Cotton cultivars even ecotypes within species differ for their temperature sensitivity. Differences in phenological stages; time requirement varied for square; flower and boll maturation are strongly influenced by environment (Singh *et al.,* 2007). Adding to the above fact, cotton cultivars respond differently to early sever heat stress due to differences in canopy development, crop growth cycle and adaptation mechanisms. Conventional cultivars sown too early, heat stress effect reproductive development (Bibi *et al.,* 2003) and cultivars shed their early reproductive parts completely and assimilates promoted excessive biomass production and affected the harvest index (Kakani *et al.,* 2005). Optimum temperature for efficient growth is reported to be 33 °C while significantly reduction in flower and boll retention has been recorded above 36 °C (Singh *et al.,* 2007). However, optimum range for different sowing window is not well defined in the country and it varies among varieties as well. Late maturing cultivars were found more vulnerable to fruit shedding when grown at higher day and night temperatures (Kakani *et al.,* 2005). Transgenic cotton (Bt.) varieties produced more bolls when sown earlier because of prolonged growing seasons (Hezhong *et al.,* 2006). Although, the performance of non Bt. varieties is good at normal (May), and sometimes during late sowing (June) as well (Akhter *et al.,* 2002; Hofs *et al.,* 2006; Arshad *et al*., 2007b). Resistance of Bt. varieties against boll worms varied under different environmental conditions and growth stages (Wang *et al.,* 2005), decreases with plant age and very low resistance has been recorded during the stages of boll development (Shen *et al.,* 2010). Climate resilient cultivars with sustainable productivity in both current and future climates would be beneficial for the cotton growers (Kakani *et al.,* 2005). On the other hand evaluation of the performance of non Bt. cultivars at earlier planting and comparison with Bt. cultivars at longer planting window (March-July) is still missing. Higher productivity can be achieved by sowing suitable cultivars at appropriate time, because it is thermo-sensitive crop so cultivar selection at different sowing time further gets prime significance. Cotton growth and seed cotton yield is dramatically affected by temperature variations (Reddy *et al.,* 2005). It exerts negative impacts on crop growth rate (CGR), leaf area index (LAI) by adversely affecting the photosynthesis (Sing *et al.,* 2007). Higher LAI contributes to high yield, attains higher CGR during the flowering periods but planting date has significant effects up to 90 days after planting. Delay in sowing achieved high values in short duration after planting than early sowing but cultivars were unable to attain the higher values (Bange and Milroy, 2008). In case of late sowing, higher temperature reduced the dry matter accretion time by accelerating crop development. Boll growth period is shortened by the higher temperature, resulting in smaller boll ultimately lower SCY (Reddy *et al.,* 2005; Pettigrew and Johnson, 2005). Environmental stresses mainly temperature is the main cause of yield variability among years; high day temperature followed by the higher night temperature may exacerbate this harmful effect (Lewis, 2000; Brown *et al.,* 2003). Unforeseen periodic incidents of heat stress are projected to happen more frequently in the region (Ahmad *et al.,* 2015). The consequence of changing weather affects the phenology, growth and development which threatens sustainable cotton production become writing on the wall. Under these circumstances, resilient varieties and optimum planting date are potential adaptations that can be considered important for sustainable seed cotton yield. The overall goal of this study was to characterize the phenology and growth of five cotton varieties (Bt. and non Bt.), selection of suitable planting date for higher production and estimation of varietal resilience to avoid the stress under uncertain environment.

MATERIALS AND METHODS

***Field experiments*:** Field experiments were conducted twice during the cotton growing season of 2012 and 2013 at research farm of Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad (31°30 N, 73°26 E and altitude 213 m). The purpose of this experiment was to evaluate the performance of promising Bt. and non Bt. cotton varieties with wider planting window (March to end of June) under irrigated semiarid environment. Planting dates and promising cotton varieties (Bt. and non Bt.) were considered as main treatments in the study. The experiments were laid out in randomized complete block design (RCBD) with split plot arrangement keeping three replicates. Cotton varieties including Bt. and non Bt. (MNH-886, AA-802, IR-3701, NIAB-9811 (NIAB-Kiran) and NIAB-112) were kept in sub plot and planting dates (10-March, 30-March, 21-April, 10-May, 1-June and 21-June) were randomized in main plots while recommended sowing at farmer's field is second week of May. Varieties IR-3701, AA-802 and MNH-886 are Bt. (*Bacillus thuringiensis*), spreading type, long stature and have longer duration while NIAB-9811 (NIAB-Kiran) and NIAB-112 are non Bt., erect type, short stature and have medium to short crop cycle.

***Environmental conditions of site*:** Experimental area experiences greater diurnal fluctuations during summer and winter seasons. It is noted for cold winter and hottest summer where temperature rise 48±2 °C during summer and minimize from 2 to 12 °C during winter season. Although weather is favorable for cotton production only during the cropping season but there is variation in minimum and maximum temperature. Rainfall variability exists, maximum rainfall occurs in monsoon during the months of July and August but it is very uncertain, and it does not coincide with production technology of cotton especially too early planting. The monthly daily values of minimum (Tmin), maximum (Tmax) and mean air temperatures, and precipitation for the period of study are presented in Fig. 1 and 2 (Pakistan Meteorology Department observatory). Soil was silty loam, brown in color, and well drained with strongly calcareous in nature. Soil has very less organic carbon in different horizons (0.89-0.42) due to its oxidation promoted by high temperature. Soil is alkaline and pH increases as depth increases and soil is nitrogen deficient (0.07%) which is decreased in subsoil. Soil bulk density is lower at upper soil and it increases with soil depth (1-1.53 g cm^{-3}).

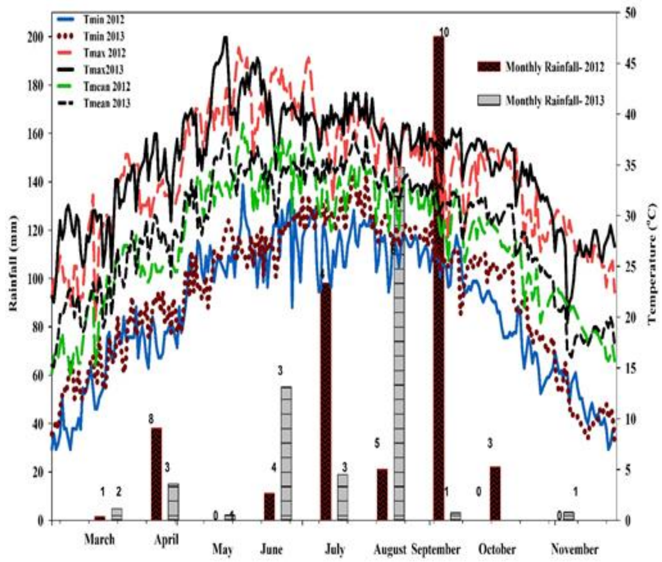

Figure 1. Climatic data; daily minimum, maximum, mean temperature and monthly rainfall with number of rainy days during cotton growing seasons (2012 and 2013).

***Crop establishment and cultural practices*:** For fine seed bed preparation recommended tillage and irrigation operations were performed during both the growing seasons. To control the weeds, Pendimethalin (33%) a pre-emergence herbicide was used at the rate of 2.5 L ha^{-1} after seed bed preparation. Cotton seed was sown on bed furrow planting method as a trend in cotton-wheat cropping zone. Seed was drilled along the edge of beds at the rate of 25 kg ha^{-1} (acid delinted). The planting density of 55,000 (plants ha^{-1}) was retained with the planting geometry of 23 cm distance from plant to plant and 75 cm between beds rows. Plant density maintenance operations such as gap filling and thinning were taken between 6-16 days after seed sowing. Insect pest infestation was controlled by adopting good agricultural practices (GAP) by spraying approved insecticide and pesticide during crop growing season to keep insect pest population below economic threshold level. All possible ways of weeds control such as manual, inter-culture and mechanical operations were adopted to avoid nutrients loss and to destroy the insect pest shelters. Soil moisture was measured in soil profile using neutron moisture meter (NMM) and recommended irrigation amount according to crop requirements was applied to avoid the water stress. Basal dose of fertilizer (P = 90 kg P_2O_5 ha^{-1} in the form of triple super phosphate and K= 50 kg K_2O ha^{-1} in the form of potassium sulphate) was applied at seed bed preparation while nitrogen 200 kg ha^{-1} (Urea) was applied in three splits, one third at sowing and rest at sympodial branching and flowering stages.

Models and Input Data Set Measurements:

***Thermal time formula model equation for cotton phenological phases*:** Cotton phenological stages were recorded by randomly tagging five plants in each experimental unit to observe calendar time of different phenological phenophases initiation such as square, flower, boll, boll opening and picking. Daily air temperatures (Tmax. and Tmin.) was used to compute thermal time requirements above a threshold temperature (TT) in terms of degrees days (DD). Thermal time was calculated with the formula equation [1] that calculates DD as the difference between the daily mean temperature and the threshold temperature (TT) for different phenological stages of cotton.

$$DD\ (°C\ days) = \sum_{i=dh}^{i=ds} [\{(Tmax + Tmin)/2\} - TT] \qquad (1)$$

Where, DD (°C days) accretion is the accumulative degrees days for specific phenophase, TT is threshold temperature which was considered as 15 °C to compute the thermal time (DD). In this case, if [(Tmax+Tmin)/2] < TT, or [(Tmax+Tmin)/2] = TT then DD was considered equal to zero (Robertson *et al.*, 2007).

Linear and quadratic models provide an opportunity to evaluate the relative contribution of each planting date in the development of field grown varieties. A linear relationship demonstrates that the thermal time procedure is suitable for the data analysis. The relationships between phenophases in duration photo thermal days and thermal time (Tt °C day) accretion for square, flower, boll initiation and boll opening (maturity) were regressed for phase duration separately for the individual cultivar. It was based on the day of year started from 10-March to 10-July for the growing seasons. Number of photo thermal day's requirement between two phenological phases was well defined using linear model while for thermal time (Tt °C day) requirement, quadratic model was used. The constants of both models were estimated through linear and quadratic regression using SAS version 9.4 (SAS Institute, Cary, NC 2013).

Crop Growth Models:

***Plant sampling approaches and model formula equations*:** Three randomly selected plants were harvested at ground levels with interval of 20 days after establishment of crop from each plot and appropriate borders were left during the both growing seasons. Fresh weight of each fraction (leaf, stem, squares, flowers and boll opened and un-opened) was recorded using sensitive electronic balance. These samples were sun dried for 48 hours and then dry weight was determined at 65 °C in an oven to a constant weight. From these measurements total dry matter (TDM) was calculated at each harvest. Similarly, an appropriate sub-sample of green leaf lamina was also used to record leaf area by leaf area meter (JVC Model TK-S310EG). Leaf area index (LAI) was calculated as the ratio of leaf area to land area. Leaf area index (LAI) model was used for daily LAI estimate as follow;

$$LAI = yo + a^{\left[e\left\{-0.5\left(\frac{x-xo}{b}\right)^2\right\}\right]} \qquad (2)$$

Leaf area duration (LAD) was estimated as (LAI_1+LAI_2) x (T_2-T_1) / 2, where, LAI_1 and LAI_2 were leaf area indices at times T_1 and T_2, respectively. Crop growth rate (CGR) was computed as (TDM_2-TDM_1) / (T_2-T_1), where TDM_1 and TDM_2 were the total dry matter harvested at time T_1 and T_2, respectively (Hunt, 1982). Mean CGR (g m^{-2} day^{-1}) was computed as (TDM_{Last} – TDM_{First}) / Total duration. Total dry matter and crop growth rate was computed by the following formulas model equations;

$$TDM = \frac{a}{1 + e\left[-\left(\frac{x - xo}{b}\right)\right]} \qquad (3)$$

$$CGR = a^{\left[e\left\{-0.5\left(\frac{x-xo}{b}\right)^2\right\}\right]} \qquad (4)$$

Finally, for calculating various observations on phenological development and growth, data was recorded from five randomly selected tagged cotton plants from each experimental unit. Final seed cotton yield was picked from whole plot. Seed cotton yield of each variety was drawn with planting time and thermal time (DDs) by using quadratic formula equation. Heat use efficiency (HUE) of seed cotton yield (SCY) was computed by regressed over the accumulation growing degree days (GDD).

$$HUE_{SCY}\ (Kg\ ha^{-1}\ °C\ days^{-1}) = SCY\ (kg\ ha^{-1}) / \sum_{i=1}^{n}[GDD]\ °C\ days \qquad (5)$$

Where, HUE_{SCY} was heat use efficiency of seed cotton yield; n was the number of days up to maturity; *i* was the *i*th day from sowing and GDD was the total accumulated growing degree days (Pandey *et al.*, 2010). Quadratic regression model was used to draw the relationship between planting data (10 March - 10 July) and HUE of seed cotton yield of each variety during growing seasons. Constants of model were estimated by using SAS version 9.4 (SAS Institute, Cary, NC 2013) for all above calculations.

***Statistical models for data analysis*:** Analysis of variance (ANOVA) for all response variables were performed based on a general linear mixed model (GLM) using SAS version 9.4 (SAS Institute, Cary, NC 2013). The effects of planting date, genotype (variety) and their interactions of both growing years separately for the photo thermal days, DDs, LAI, LAD, TDM, CGR, SCY and HUE_{-SCY} were established using the following general linear mixed (GLM) model:

$$Y_{ijk} = \mu + \int_i + PD_j + \epsilon a_{ij} + G_k + PD \times G_{jk} + \epsilon b_{ijk} \qquad (6)$$

Where Y_{ijk} was the dependent variable subjected to the *i*th level of ∫, *j*th level of planting date (PD) and *k*th level of G in the *i*th block; ∫ was the block effect, PT was the planting time effect, ϵa_{ij} was the error (a) for block with planting time, G was the genotype effect (variety) and ϵb_{ijk} was the general experimental error.

$$Y_{ijkl} = \mu + \int_i + Y_j + \epsilon a_{ij} + PD_k + PD\times Y_{jk} + \epsilon b_{ijk} + G_l + G\times Y_{jl} + G\times PD_{kl} + G\times PD\times Y_{jkl} + \epsilon_{cijkl} \quad (7)$$

Where Y_{ijkl} was the dependent variable subjected to the *i*th level of $\int$, *j*th level of year, *k*th level of PD and *l*th level of G in the *i*th block; $\int$ was the block effect, Y was the year effect, ϵa_{ij} was the error (a) for block with year, PD was the planting date effect, ϵb_{ijk} was the error (b) for planting date with year including block effect, G was the genotype effect (variety) and ϵc_{ijkl} was the general experimental error. Data was analyzed with block, year, planting date, genotype, and the interactions among years, planting date, and genotype while year as fixed effect in the model while block × planting date and block × genotype were considered random. Interaction for year analysis was computed by using model (7) as year × block, year × planting date, planting date × block × year, genotype × year, genotype × planting date and genotype × year × planting date. While for separate year analysis, interaction was computed as block × planting date and genotype × planting date (model 6). Honest significant difference test (HSD) mean comparison were used to distinguish differences between treatment means and were considered significant if P≤0.05 and P≤0.01. Compound symmetry or first order autoregressive was used to model covariance between years for each of the response variables. Linear and quadratic regression formula model equations were used for the computation of development, growth and yield on daily planting basis using SAS and Sigma plot software.

RESULTS

***Climatic variables*:** A semi-arid climate has characteristics of high temperature, low precipitation below than potential evapotranspiration and uncertain in weather conditions and higher risk for crop production. The cotton crop growth and development is highly sensitive to climate, early and late chilling temperature, high stress at peak reproductive stage, rainfall variability during growing season, unexpected extreme weather events may lead to productivity loss in cotton. Similar trend of mean temperature was observed during growing seasons, lower at early planting, rising to peak in June and then decreasing to the end of season. The 2013 early growing season (March-April) was favorable (warmer) for early sowing while 2012 late growing season was promising for cotton growth and development for late sowing (Fig. 1). Thermal time accretion (°C days) was found high in early months (March-May) of 2013 than 2012 whereas it was also computed high during late growing season (November) in 2012 than 2013. Lower night temperature is most detrimental for growth and reproductive phenological stages, more number of nights <12 °C was observed (20) in early 2012 season (March) as compared with 2013 (5 nights). Early planting in 2012 suffered chilling temperature; 5 days recorded less than threshold temperature than 2013 growing season. Maximum number of days with temperature >35 °C observed in 2012 (May-August) growing season than 2013 (Fig. 2). Highly rainfall variability observed between growing seasons, high intensity rainfall occurred during 2012 season (September) while 2013 rainfall was less intensive and coincide with the production technology of mostly planting (Fig. 1). Similar trend for monthly reference evapotranspiration (ET_o) and solar radiation (MJ m^{-2} day^{-1}) was observed during both growing seasons, it gradually increased in early months, peak during May to June then decreased progressively at the end of growing seasons (Table 1). Higher solar radiation was observed during 2013 growing season as compared with 2012 (Fig. 2).

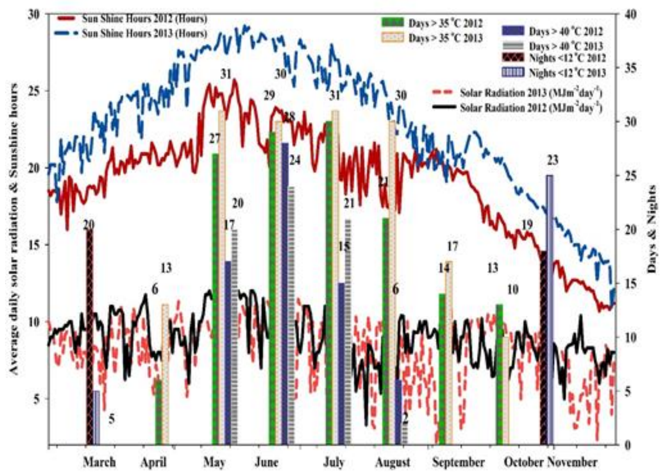

Figure 2. Mean daily solar radiation, sun shine hours and number of nights <12°C, days >35°C and >40°C during two experimental growing seasons (2012 and 2013).

Phenology, Crop development and Crop cycle:

***Days to cotton phenological phases*:** Crop phenology, growth and crop cycle were determined by environmental conditions of growing season. Changes in phenological events were controlled by weather conditions especially temperature. A clear tendency of longer and shorter duration for phenological phases was observed with early and late sowing respectively. Similar trends were observed in growing seasons although 2012 was cooler during early planting took more days than 2013. Early sowing experienced low temperature (cold shock) at key phenological phases than 10-May planting, while late (1-June and 21-June) confronted heat stress during developmental stages. Increase in temperature accelerated the phenological development for all phenophases among varieties. First square, flower, boll and boll opening of early sown cotton (10-March, 30-March and 21-April) were delayed 3-10, 5-13, 3-14 and 2-13 days respectively as compared with 10-May planting (37, 53, 77 and 103 days) in 2012. As the sowing time delayed from May to onward, crop was exposed to high temperature stress and longer

Table 1. Weather data of experimental site during cotton growing seasons.

Weather variables	T min. (°C)		T max.(°C)		T mean (°C)		Cumulative day degrees (°C days)		Cumulative solar radiation (MJm^{-2})		Cumulative sunshine (hours)		Cumulative Evapotranspi-ration (mm)	
Month	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**	**2012**	**2013**
March	11.27	13.41	25.52	27.80	18.39	20.61	90.45	153.20	575.30	639.80	241.80	280.00	134.80	125.10
April	17.60	19.41	33.38	33.69	25.49	26.55	291.25	334.35	618.10	728.50	241.15	282.50	163.00	177.30
May	24.32	24.36	39.30	40.31	31.81	32.34	498.45	525.15	711.40	850.00	299.20	304.00	193.40	233.20
June	27.48	27.26	42.20	41.06	34.84	34.16	574.75	564.75	686.30	841.00	279.05	326.50	253.60	215.90
July	27.35	30.58	39.23	39.69	33.29	35.13	549.70	609.05	648.70	820.80	264.10	249.60	221.30	208.80
August	27.04	28.80	37.00	37.96	32.02	33.38	515.70	553.61	566.80	730.80	211.20	237.30	180.90	163.00
September	24.26	25.48	34.14	36.80	29.20	31.14	409.45	484.40	581.60	655.30	218.40	263.50	129.50	163.10
October	17.36	21.11	32.06	33.56	24.71	27.33	322.65	360.75	474.77	580.85	266.95	233.85	108.00	115.60
November	11.83	11.09	27.85	26.52	19.85	18.81	118.95	92.21	364.80	454.30	191.80	233.51	74.90	73.30

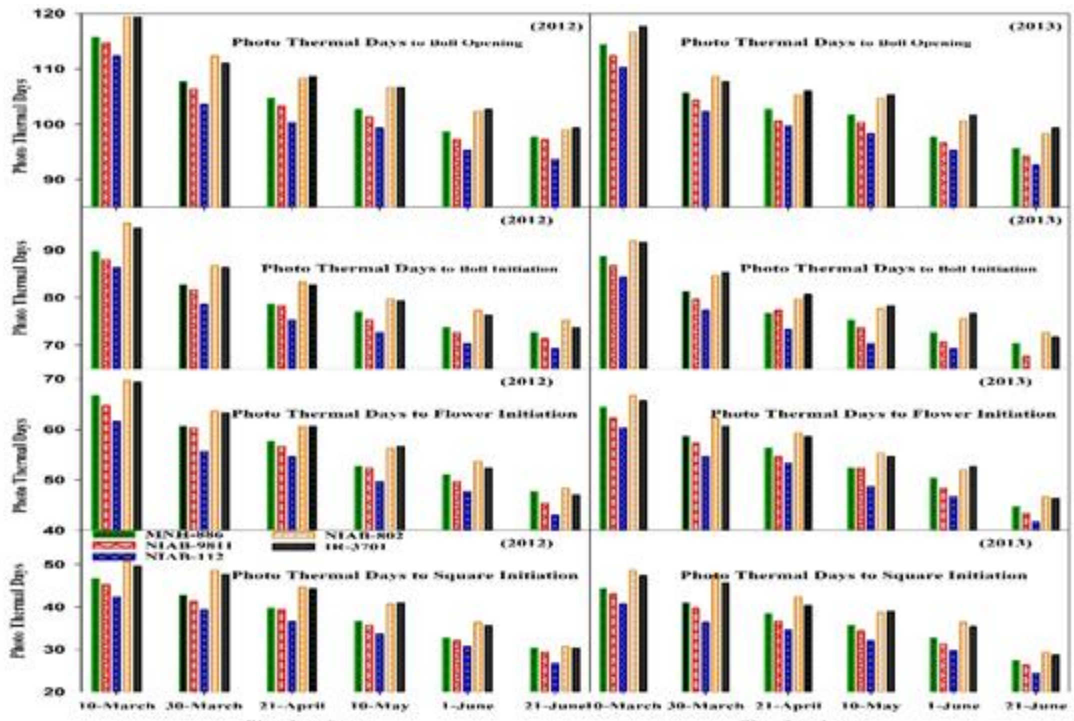

Figure 3. Photo thermal days to square, flower, boll initiation and boll opening at different planting dates during both growing season (2012 and 2013).

photoperiod, resulting in the shortening of duration for all key phenological stages especially boll development. Late sowing (1-June and 21-June) also challenged high temperature at early phenological phases and first square, flower, boll and boll opening were advanced 4-8, 3-7, 2-4 and 4-6 days respectively in 2012. Similar trend was observed in 2013 but all phenological stages were advanced (early) 0-3 days than 2012 for both early and late sowing due to temperature variation. Good statistical indices with lowest root mean square error (RMSE) and higher coefficient of determination (R^2) were observed for all phenological phases during growing seasons 2012 and 2013 (Fig. 3). Significant difference among varieties was recorded due to variation in phenotypic characteristics and growth behavior. Varieties categorized in short, medium and long duration due to variation in growth cycle. Six sowing dates provide a wider range of climatic conditions to evaluate the performance of the varieties. Short duration variety (NIAB-112) attained 6-8 less days for all phenological events than longer duration varieties (AA-802 and IR-3701) during both growing seasons. Linear model of each variety demonstrated strong relationship with decreasing trend between days of the growing seasons (started from 10-March) with photo thermal days after sowing for all key phenological phase during growing seasons. Lower RMSE (0.618-2.37 days) and higher determination coefficients (0.85-0.99) was recorded for all phenological

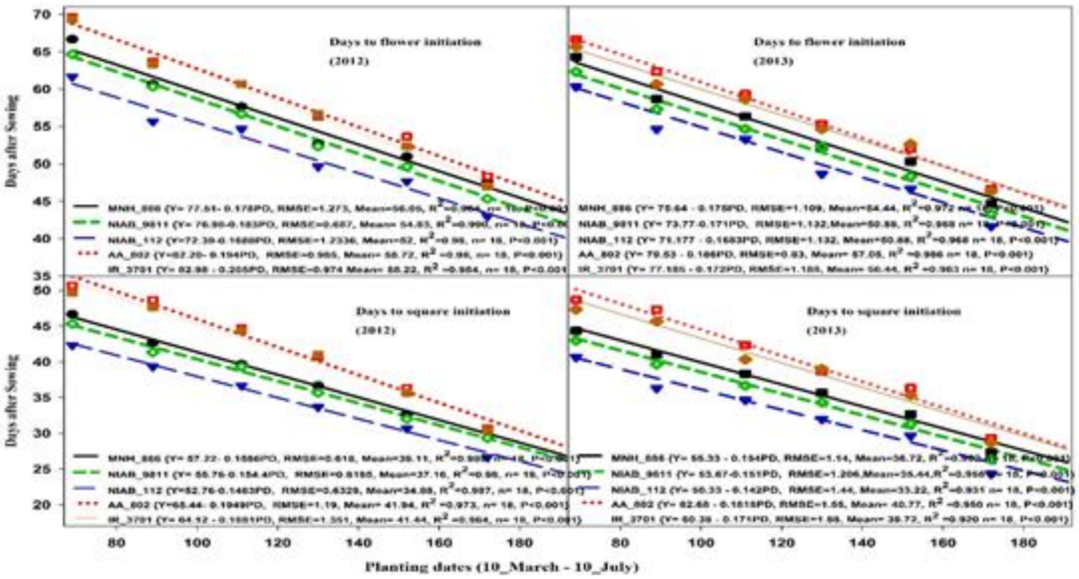

Figure 4. Photo thermal days of cotton varieties to square and flower initiation phases at different planting dates (calendar days: 10-March to 10-July) during growing seasons (2012 and 2013).

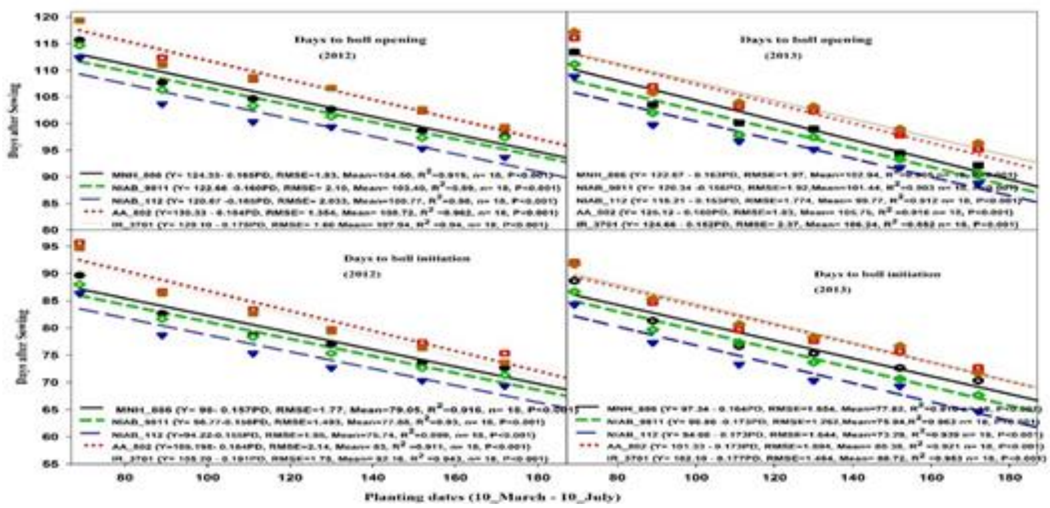

Figure 5. Photo thermal days of cotton varieties to boll initiation and boll opening phases at different planting dates (calendar days: 10-March to 10-July) during both growing season.

stage for both growing seasons indicating the good assessment of model (Fig. 4 and 5).

***Thermal time (degree days) of cotton phenological phases*:** Each phenological phase required specific heat units for its completion and enters into another phenophase above a threshold temperature. Thermal time of phenological phases was estimated using thermal time model. It predicts the development of a variety as a function of temperature assuming a linear relationship between temperature and the development rate. Strong and positive linear relationship was observed between temperature and thermal time accretion. Thermal time accumulated gradually and attained peak in 10-May sowing then decreased with increasing trend up to end planting date during both growing seasons. Quadratic trend was observed in degree day's accretion, although early sowing (10 and 30-March) took 14 more photo thermal days for key phenological stages but temperature increasing rate is too high so early sowing accumulated less thermal time than others. April to June planting windows experienced heat stress (>40 °C), attained higher excessive thermal unit in less time than others. Higher difference (46 and 33%) for day degrees accretion was computed for early phenological phases (square and flower initiation) while lower (20 and 13%) for boll initiation and boll opening respectively in comparison with 10-May and 10-March in 2012. Similar trend was computed in 2013 but with less difference among planting dates due to lower number of photo thermal days were taken to accomplish phenological phases however significant difference was observed at boll initiation and boll opening phases between growing seasons (2013 > 2012). Lower RMSE (9.96-12.56 °C days) and higher determination coefficients (> 0.99) were observed for all phenological phases for growing season (Fig. 6). Longer crop cycle varieties delayed in reproductive initiation, accumulated higher day degrees for phenological phases than short one. Significant differences were computed among varieties for all phenological phases during seasons due to genotypic variations and their growth behavior. Varieties IR-3701 and AA-802 being longer growth duration accumulated higher degree days (17, 12, 10, and 6% for square, flower, boll initiation and boll opening phases, respectively) than short one (NIAB-112) in 2013. Similar trend was recorded in 2012, as crop advanced to higher phenological phase's lower difference computed due to increase in temperature. High variation of 6, 39, 29 and 19% in thermal time accretion was recorded with in treatments for square, flower, boll initiation and boll opening respectively due to longer planting window and difference in cultivars growing cycle. Strong quadratic relationship between days of growing seasons and thermal time accretion was computed among cultivars for all key phenological phases during both growing season. Longer duration varieties accumulated higher day degrees in 10-May and 1-June planting for all phenophases while lower for short duration varieties at 10 and 30-March planting due to lower

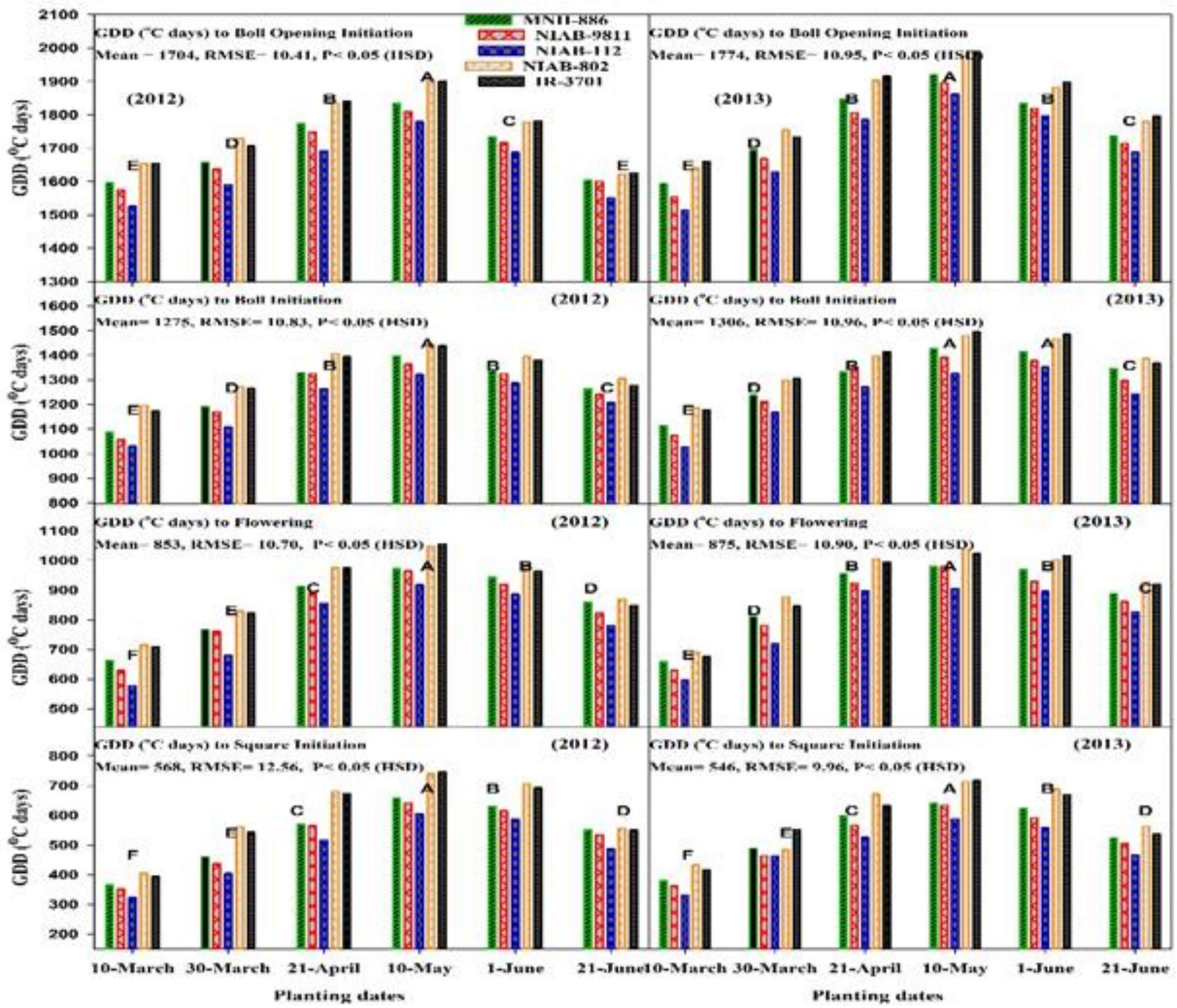

Figure 6. Cumulative degree days (°C days) up to square, flower, boll initiation and boll opening phases of cotton at different planting dates during both growing season (2012 and 2013).

temperature early in the season while late planting faced heat stress (>40 °C) at all phenological phases. Prediction of each variety model was good and accurate with good statistical indices of RMSE (11-39 °C days) and R^2 (0.88-0.99) at all phenological phases during growing seasons (Fig. 7 and 8).

Growth Indices:

***Leaf area index (LAI)*:** Efficient utilization of light energy and conversion efficiencies depend on radiation absorption by the green leaves because solar energy and capturing efficiency determine the production. Significant differences

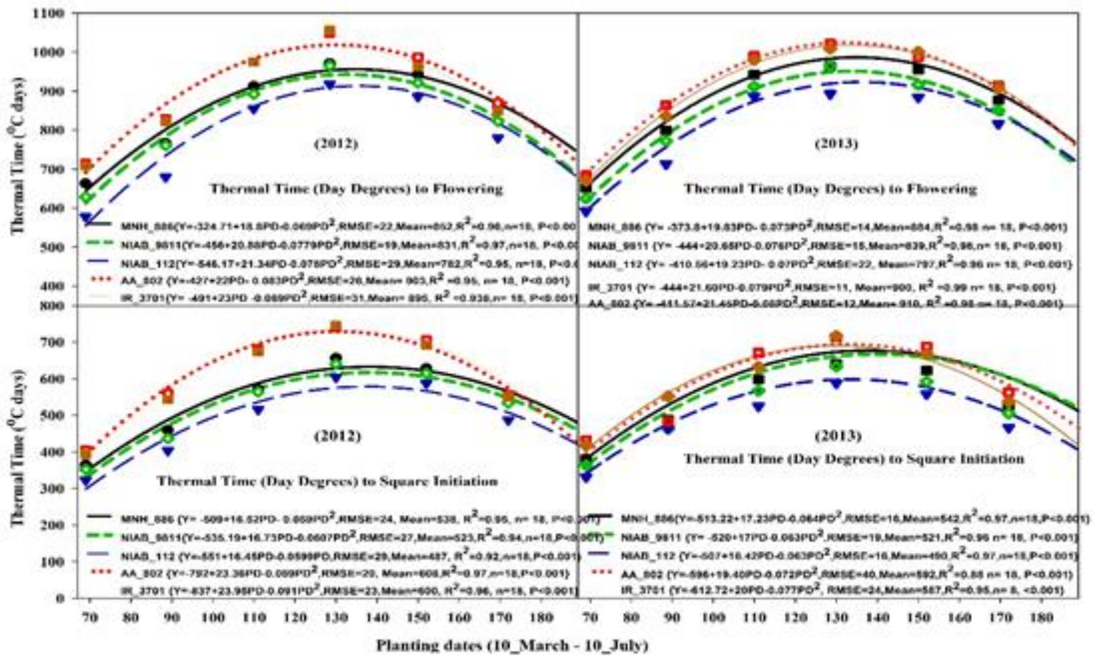

Figure 7. Thermal time (°C days) of cotton varieties to square and flower initiation phases at different planting dates (calendar days: 10-March to 10-July) during both growing seasons (2012 and 2013).

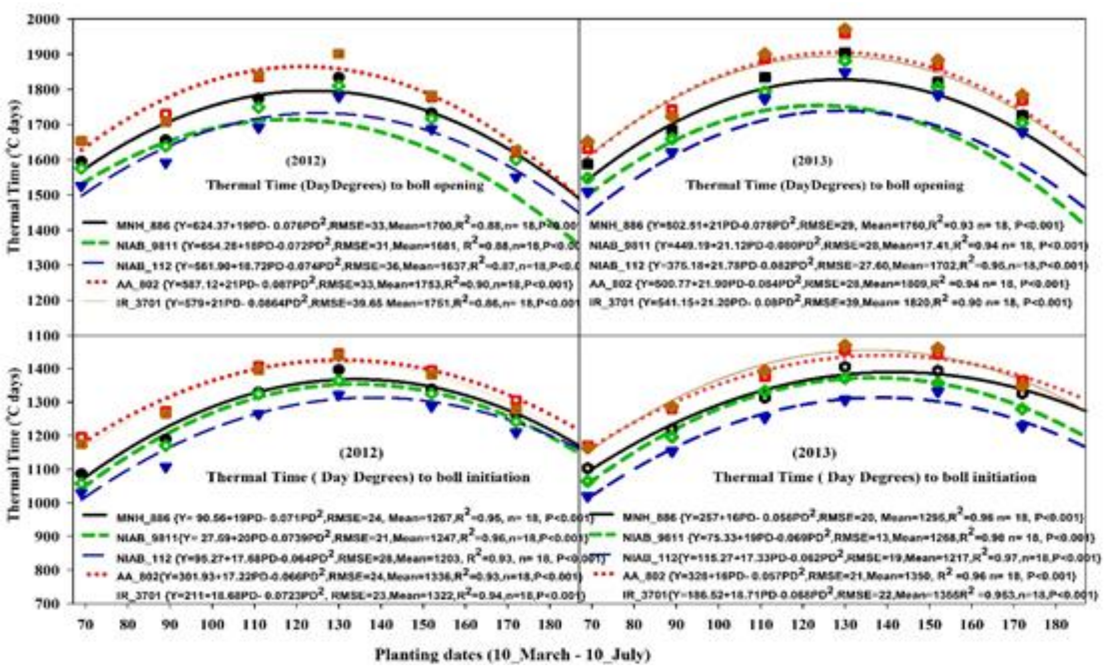

Figure 8. Thermal time (°C days) of cotton varieties to boll initiation and boll opening phases at different planting dates (calendar days: 10-March to 10-July) during both growing season.

were found among planting dates and varieties during both growing season. Leaf are index increased progressively up to reproductive phase attained peak thereafter showed a declined trend with increasing ratio, and significant variation in leaf growth pattern with passage of time was accounted among plating dates.

It exerted high effect on LAI growth, early planting dates (10 and 30-March) had lower growth during early seasons experienced poor heat unit accretion, reached to peak very late in the season (110-120 days after planting) while 21-April and 10-May planting attained maximum LAI up to 90-100 DAP. Delay sowing (1-June and 21-June) had a clear effect on leaf growth due to excessive photo thermal and heat index accumulation, attained peak in 80-90 days after planting for

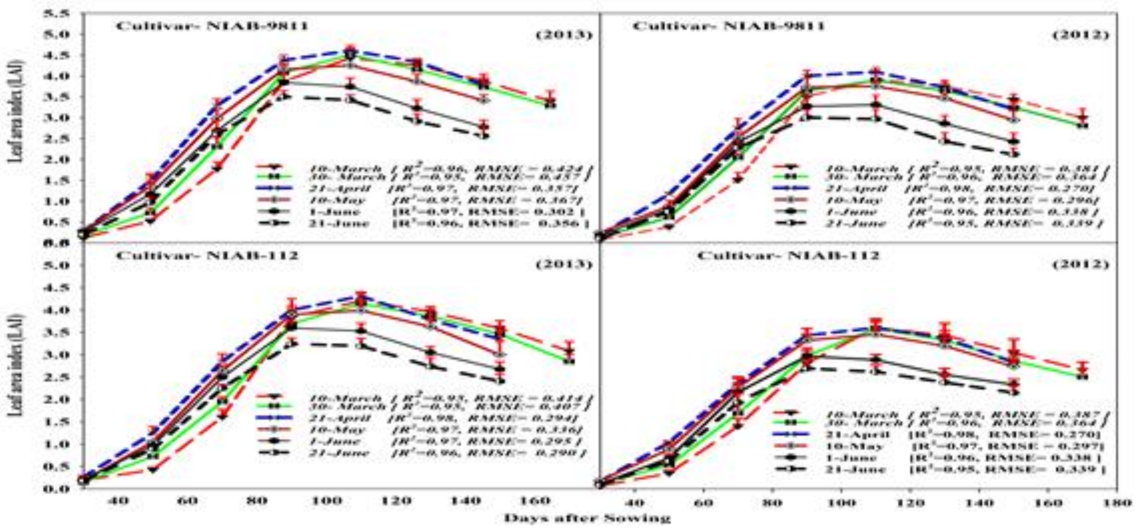

Figure 9. Leaf area index (LAI) of cotton varieties (NIAB-9811 and NIAB-112) at different planting dates during both growing season (2012 and 2013).

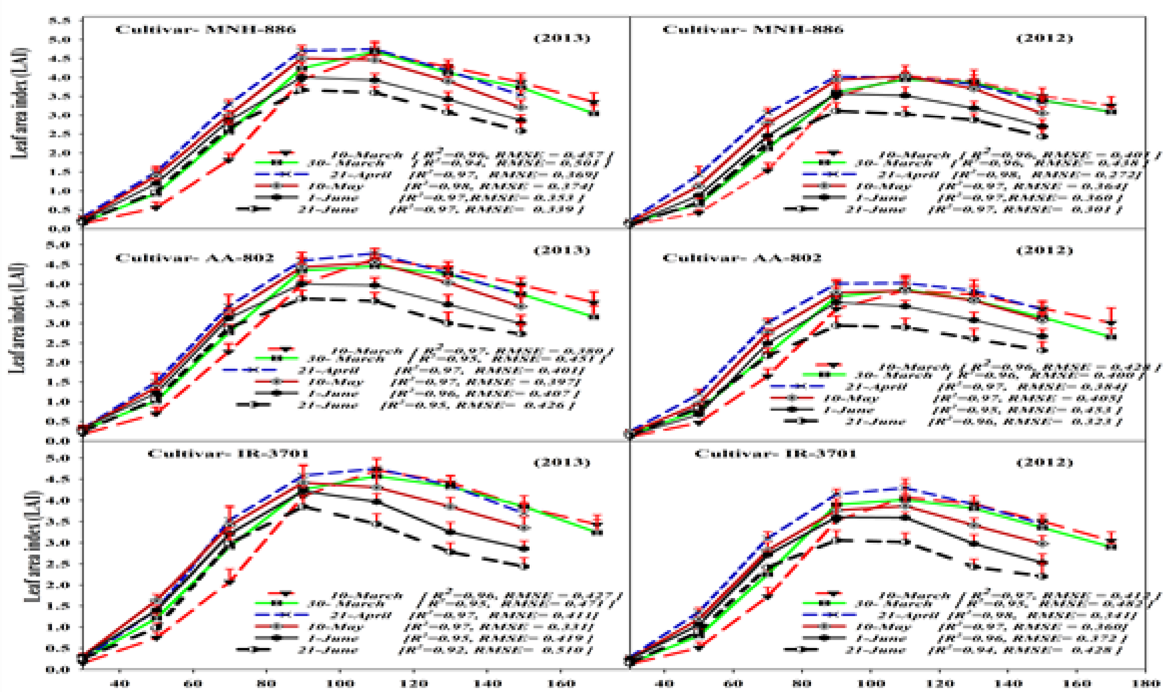

Figure 10. Leaf area index (LAI) of cotton varieties (MNH-886, AA-802 and IR-3701) at different planting dates during both growing season (2012 and 2013).

all varieties in both season (Fig. 9 and 10). Planting at 10-March, 30-March and 21-April attained significantly higher LAI (4.41, 4.34 and 4.52) from pooled data of seasons while lowest in 21-June planting (3.38). Planting at 10-March attained peak LAI (4.41) although very late in the season but it was 24% higher than 21-June planting by the reason of more photo thermal and solar radiation accumulation during flower and boll development phases. Growing years had significant variation (6.34%) due to variation in environmental conditions. Genotypic variations exist in maximum LAI; broad leaves varieties (MNH-886, IR-3701 and AA-802) attained more LAI than medium one (NIAB-9811 and NIAB-112) at all planting during both growing season. Leaf growth variation observed within the seasons, it ranged 13.80 to 19.45% differences among varieties. Generally lower RMSE (0.24) and higher R^2 (0.88) was observed when all data was included (Table 2). Good statistical indices [(RMSE= 0.27 – 0.51), R^2 = (0.92–0.98)] were computed for in seasons LAI analysis at different planting windows and varieties during field experiments reveled the close association between observed data and modeled one (Fig. 9 and 10).

***Dry matter production (kg ha^{-1})*:** Significant differences were found in total dry matter (TDM) production among planting dates and varieties during the growing seasons. There were 33 and 30% variation in biomass production among planting dates in 2012 and 2013 growing season respectively. The higher TDM (6.30%) was produced in 2013 than first growing year (2012) was probably due to higher solar radiation, heat unit accretion and higher total sunshine hours. Seasonal growth analysis revealed high variation among planting dates, significantly low biomass accumulation was observed in 10-March planting (Fig. 11 and 12) especially too early in the growing season in all varieties due to poor heat unit accumulation, less solar radiation and short sun shine hours (Fig. 2). But finally it attained 32% higher biomass than 21-June planting due to longer growing season by utilizing high photo thermal index and solar radiation at later growth stage (Table 2). Linear and strong association was regressed between accumulated thermal time and in season dry matter accumulation for all varieties at different planting windows during both growing seasons (Fig. 13). Similar trend as LAI was also observed in biomass accumulation among varieties

Table 2. Effect of planting dates on growth, seed cotton yield and heat use efficiency of cotton varieties during growing seasons.

Treatments	Leaf Area Index (Peak)			Total dry matter (kg ha^{-1})			Mean CGR (g m^{-2} day^{-1})			Seed cotton Yield (Kg ha^{-1})			HUE-SCY (Kg ha^{-1} °C days^{-1})		
Planting Dates	**2012**	**2013**	**Pooled**	**2012**	**2013**	**Pooled**	**2012**	**2013**	**Pooled**	**2012**	**2013**	**Pooled**	**2012**	**2013**	**Pooled**
10-March (69 CD*)	4.30 a	4.53 ab	4.41 AB	13573 a	14173 a	13873 A	8.90 a	9.12 a	9.03 A	3502 b	3871 b	3687 B	1.50a b	1.61 a	1.55 ab
30-March (89 CD)	4.21 ab	4.47 ab	4.34 AB	13093 ab	14373 a	13733 A	8.61 ab	9.23 a	8.94 A	3608 ab	3948 ab	3778 AB	1.53 ab	1.60 a	1.56 ab
21-April (111 CD)	4.41 a	4.63 a	4.52 A	12940 ab	14033 a	13487 AB	8.75 ab	9.22 a	8.99 A	3714 a	4113 a	3913 A	1.55 a	1.62 a	1.59 a
10-May (130 CD)	4.15 ab	4.30 b	4.22 B	12140 b	13000 b	12570 B	8.29 b	8.38 b	8.35 B	3581 ab	3977 ab	3780 AB	1.46 b	1.54 a	1.49 b
1-June (152 CD)	3.78 b	3.85 c	3.81 C	10600 c	11253 c	10927 C	7.01 c	7.30 c	7.14 C	3076 c	3310 c	3193 C	1.35 c	1.35 b	1.35 c
21-June (172 CD)	3.27 c	3.48 d	3.38 D	9147 d	9800 d	9473 D	6.02 d	6.31 d	6.15 D	2192 d	2491 d	2341 D	1.08 d	1.11 c	1.09 d
HSD 0.05	0.46	0.30	0.26	1223	899	954	0.54	0.57	0.45	234	198	255	0.06	0.12	0.068
Significance	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
Cotton Varieties (Bt. and non Bt.)															
MNH-886 (Bt.)	4.2 ab	4.34 a	4.25 A	12144 ab	13378 ab	12761 AB	8.24 a	8.66 ab	8.46 AB	3651 a	4050 a	3850 A	1.57 a	1.63 a	1.60 a
NIAB-9811 (Non Bt.)	4.0 b	4.20 ab	4.06 B	11561 b	12467 b	12014 B	7.91 a	8.06 b	7.96 B	3526 a	3839 a	3682 A	1.53 a	1.56 ab	1.55 a
NIAB-112 (Non Bt.)	3.6 c	3.92 b	3.74 C	10389 c	10778 c	10583 C	7.04 b	7.02 c	7.05 C	3244 b	3588 b	3415 B	1.43 b	1.49 b	1.46 b
AA-802 (Bt.)	4.2 ab	4.28 a	4.20 A	12600 a	13322 ab	12961 A	8.19 a	8.71 a	8.47 A	3006 bc	3296 c	3151 C	1.26 c	1.34 c	1.30 c
IR-3701 (Bt.)	4.21 a	4.26 a	4.26 A	12883 a	13917 a	13400 A	8.26 a	8.84 a	8.57 A	2970 c	3383 bc	3176 C	1.24 c	1.32 c	1.29 c
HSD 0.05	0.26	0.32	0.18	924	952	854	0.49	0.64	0.50	241	209	250	0.07	0.12	0.074
Significance	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
Mean	4.03	4.22	4.13	11940	12734	12337	7.93	8.27	8.10	3280	3618	3449	1.41	1.47	1.44
R^2	0.99	0.97	0.98	0.92	0.96	0.94	0.91	0.92	0.92	0.95	0.93	0.94	0.93	0.93	0.93
RMSE	0.31	0.46	0.38	878	943	883	0.35	0.48	0.39	203	273	241	0.08	0.09	0.09

Mean sharing different letters in a column differ significantly at $p \leq 0.05$ *, ** = significant and highly significant respectively; NS = Non-Significant, HSD=Honest Significant Difference Test, HUE-SCY= Heat use efficiency seed cotton yield, and CD* Calendar day

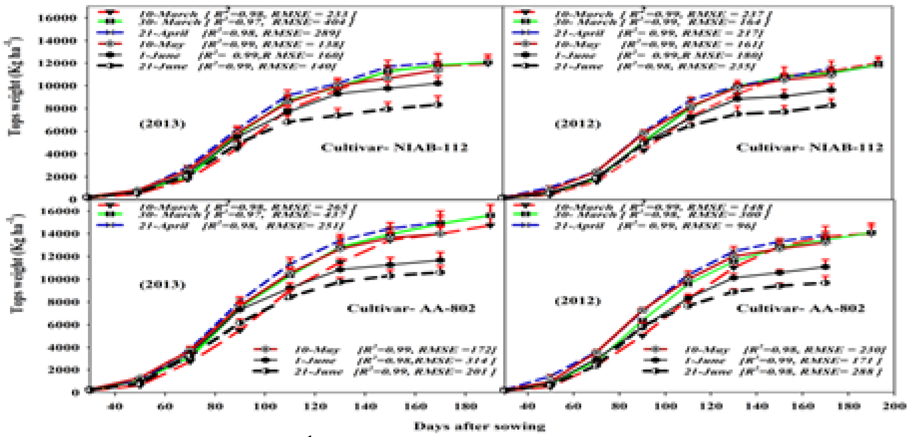

Figure 11. Dry matter accumulation (kg ha^{-1}) of cotton varieties (NIAB-112 and AA-802) at different planting dates during both growing season (2012 and 2013).

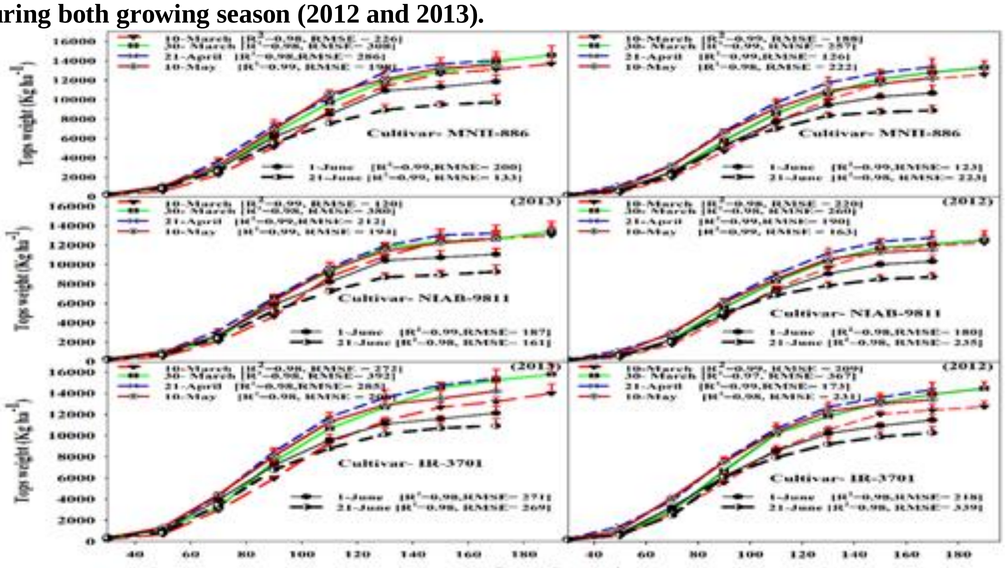

Figure 12. Dry matter accumulation (kg ha^{-1}) of cotton varieties (MNH-886, NIAB-9811 and NIAB-112) at different planting dates during both growing season (2012 and 2013).

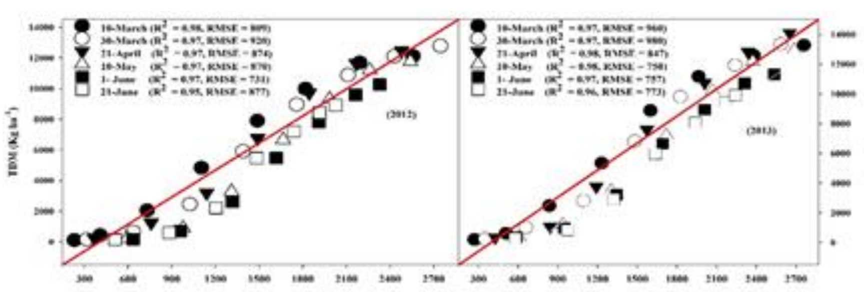

Figure 13. Relationship of in seasons dry matter accumulation with respective thermal time (°C days) at different planting windows (10-March – 21-June) using pooled data of all cotton varieties during growing seasons (2012 and 2013).

due to genotypic variations, NIAB-112 produced 19 and 22% lower biomass than broad leaves IR-3701 (12883 and 13917 kg ha^{-1}) in 2012 and 2013 growing season, respectively, while NIAB-9811 ranked second in final biomass production (11516 and 12467 kg ha^{-1}) during both seasons of planting (Table 2). Lower RMSE (5%) and satisfactory good determination coefficient (0.88 and 0.89) were computed in 2012 than 2013 due to overall less biomass production in first growing season (11940 < 12734 kg ha^{-1}). There was minor differences between observed and modeled in seasonal TDM accumulation with lower RMSE ranged 96 to 437 kg ha^{-1} and higher coefficient of determination (0.97-0.99) for all studied factors during both year of filed experiments (Fig. 11 and 12).

***Crop growth rate (g m^{-2} day^{-1})*:** The crop growth rate (CGR) is regarded as one of the most significant growth functions that represent the dry matter accretion with time. It presented a bell shaped distribution trend along the season while it attained peak differently at planting seasons (Fig. 14 and 15) but generally 12-35 days after the flowering phase initiation period then decreasing until the end of season. Higher variation in crop growth trends was computed due to longer planting windows experienced variation in seasonal weather

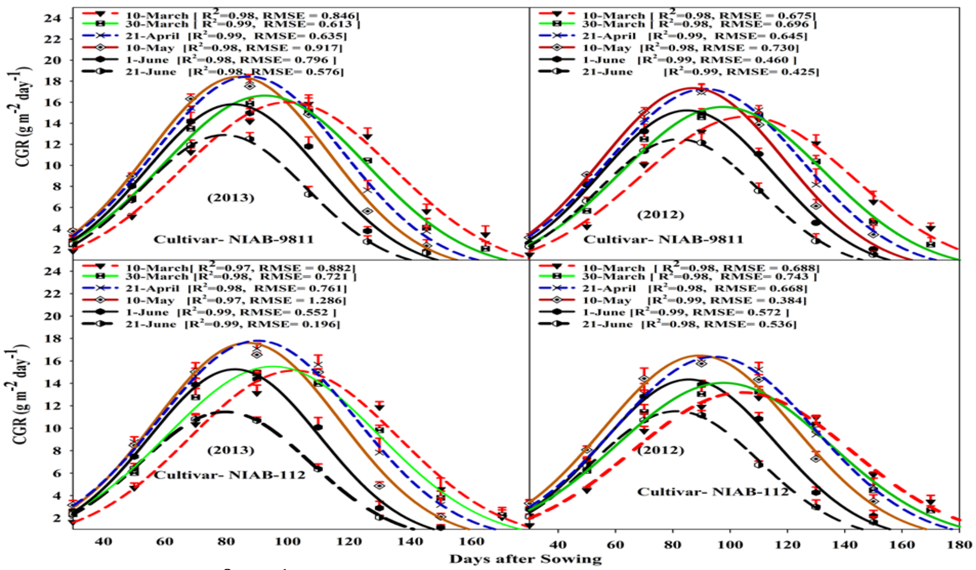

Figure 14. Crop growth rate (gm^{-2}day^{-1}) of cotton varieties (NAIB-9811 and NIAB-112) at different planting dates (10-March – 21 June) during both growing season (2012 and 2013).

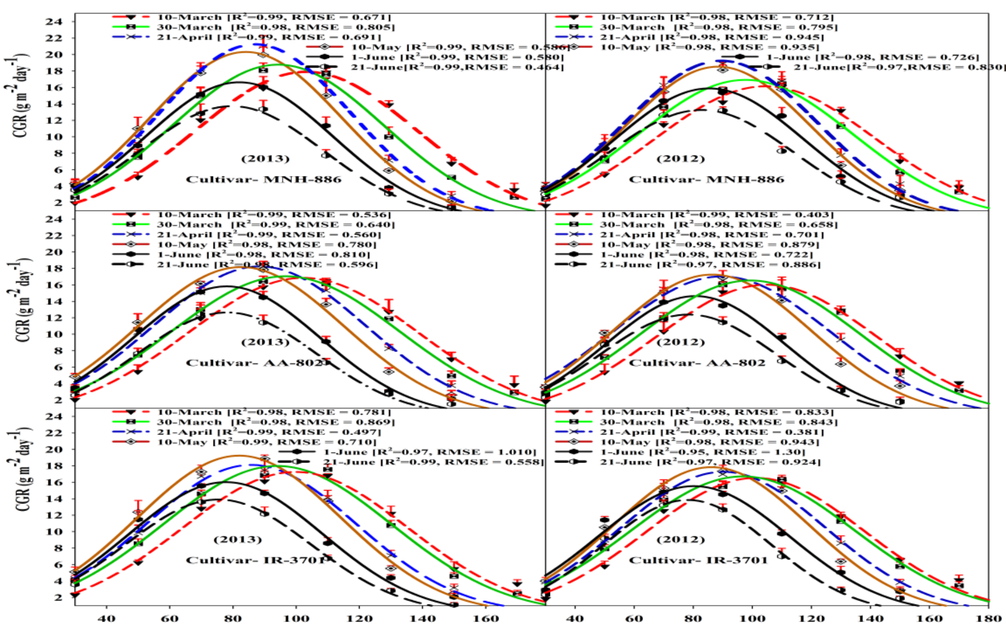

Figure 15. Crop growth rate (gm^{-2}day^{-1}) of cotton varieties (MNH-886, AA-802 and IR-3701) at different planting dates (10-March – 21 June) during both growing season (2012 and 2013).

conditions. Late planting (21-June) attained peak CGR early in the season, while 10-March planting achieved peak phase up to 110 DAP for all varieties during years. Genotypic variation exist among varieties, short duration NIAB-112 attained peak CGR, 10 days earlier while 90-100 days were taken by NIAB-9811 after planting. Longer duration varieties (IR-3701, AA-802 and MNH-886) took 90-110 days to attained peak CGR after planting in case of 30-March planting. A close fit was obtained between observed and modeled data for each variety in all planting windows with good statistical indices [(RMSE= 0.19-1.29), (R^2 = 0.95-0.99) revealed the robustness of the model during both crop growing years (Fig. 14 and 15). Higher mean CGR (9.03-8.94 g m^{-2} day^{-1}) was recorded in 10-March to 21-April planting followed by 10-May (8.35 g m^{-2} day^{-1}) while lowest (6.15 g m^{-2} day^{-1}) was observed in 21-June planting when pooled data was considered. Significantly higher mean CGR (8.57, 8.47 and 8.46 g m^{-2} day^{-1}) was attained by IR-3701, AA-802 and MNH-886 respectively followed by NIAB-9811 (7.96 g m^{-2} day^{-1}) and there was 18% variation recorded among verities (Table 2). It might be due to differences in genotypic nature and canopy structure (broad and medium sized leaves) among varieties.

***Seed cotton yield (kg ha^{-1})*:** Seed cotton yield (SCY) varied from 2192 kg ha^{-1} to 4113 kg ha^{-1} depending on planting window and varietal type. Planting date effect on seed cotton yield was highly significant (p<0.01) during both year with 21-April planting yielded higher (40%) than delayed planting on 21-June (2341 kg ha^{-1}) and 20 days early (30-March) and late planting (10-May) were not statistically different. Significant variations were found among varieties, MNH-886 yielded 18% higher (3850 kg ha^{-1}) as compared with AA-802 and IR-3701 when pooled effect was considered. Seasonal variations still exists, 9.34% higher seed cotton yield was observed in 2013 than 2012 due to significant differences in weather conditions (Table 2). Clear tendency of decreasing trend in SCY with delayed planting after 10-May was observed while similar was observed for 10-March planting where cold shock and sub optimal environmental conditions were confronted with potential yield (Fig. 16 and 17).

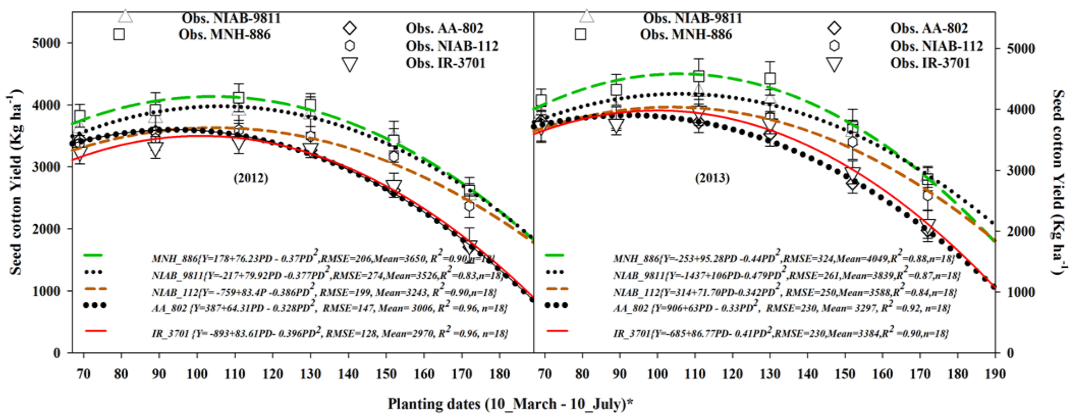

Figure 16. Seed cotton yield (kg ha^{-1}) of cotton varieties at different planting dates (calendar days: 10-March to 10-July) during both growing season (2012 and 2013).

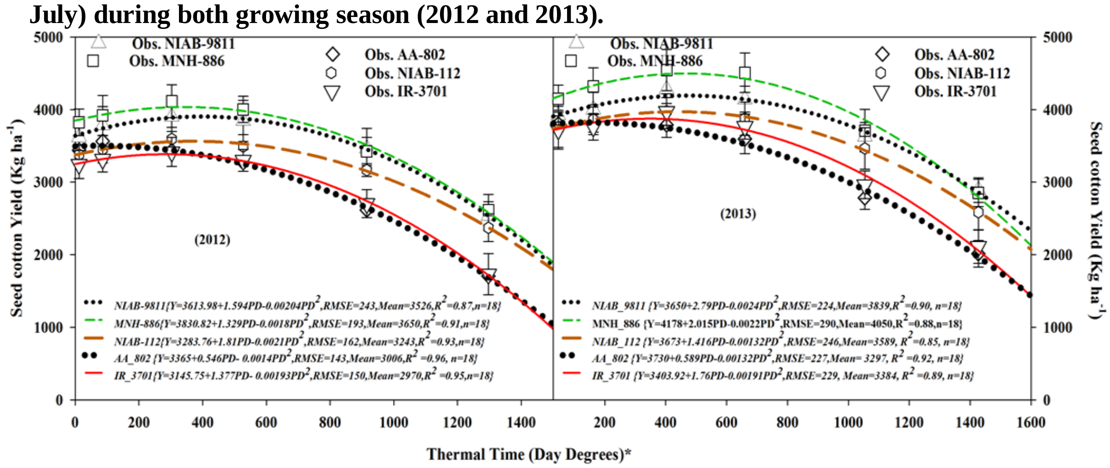

Figure 17. Seed cotton yield (kg ha^{-1}) of cotton varieties at different thermal time (day degrees) during both growing season (2012 and 2013).

Significant quadratic association between days of planting season (started 10-March) and thermal time (°C days) with seed cotton yield were computed during both growing years using regression model for each variety. Models prediction were good and reliable to quantify the daily seed cotton yield against planting windows for each variety, clear decreasing trend of yield was observed against planting dates when it delayed from 10-May. Genotypic variation in yield evidently depicted planted at variable planting windows during both growing years due to significant variation in environmental conditions within the growing season. Planting trend of AA-802 seemed to be shifted early in the year (92-100 calendar day) than others while MNH-886 and IR-3701 produced maximum yield at planting window of 102-108 CD. Longer but late planting windows (102-112 CD and 107-112 CD) for potential yield were observed in NIAB-112 and NIAB-9811 for pooled data of both growing season.

Model prediction accuracy and reliability can be assessed by the good statistical indices with lowest RMSE (128-324 kg ha^{-1}) and higher coefficient of determination (0.83-0.96) for all yield data studied (Fig. 16). Better predictions were observed for the thermal yield model for each year (Fig. 17) with a strong quadratic association between thermal time and seed cotton yield. Best fit of thermal time to corresponding potential seed cotton yield was obtained by using thermal model. According to the model results, maximum seed cotton yield was attained differently for each variety due to genotypic variations (Fig. 17). Similar trend as photo thermal model was also observed here but it had clear picture regarding both thermal time and calendar days to find optimum seed cotton yield. Variety AA-802 attained its maximum high seed cotton during planting window of 95-104 and 90-98 CD, 145-241 and 170-245 °C days for 2012 and 2013 growing seasons respectively while later planting window was observed in case of NIAB-9811 required higher thermal time and photo thermal days [(115-124 and 121-130 CD) and (340-431 and 522-625°C days)]. Higher seed cotton yield was produced by MNH-886 during planting window of 110-124 CD and 110-120 CD, 294-431 and 389-500 °C days for 2012 and 2013 years respectively (Fig. 16 and 17) while cultivar IR-3701 attained its maximum seed cotton yield little bit early in days and thermal time than NIAB-9811 during both year. Lower RMSE (143-290 kg ha^{-1}) and good coefficient of determination (0.85-0.96) was computed for thermal time yield model during both growing season with varieties (Fig. 16). Relationships of leaf area duration (LAD) were regressed for TDM and seed cotton yield at all planting dates with varietal data indicated the best fit with strong linear association had good statistical indices [(SE=672 and 665 Kg ha^{-1}), (R^2= 0.89 and 0.85), (r = 0.94 and 0.92)] and [(SE=270 and 288 Kg ha^{-1}), (R^2= 0.86 and 0.81), (r = 0.93 and 0.90)] for TDM and seed cotton yield during 2013 and 2012 growing years, respectively (Fig. 18).

***Heat use efficiency-seed cotton yield (HUE_{SCY})*:** Significantly higher reduction (31 %) was computed with delayed in planting (21-June) than 21-April (1.59 kg ha^{-1} °C days^{-1}) in HUE_{SCY} with pooled data analysis. Early planting (10-March to 21-April) produced significantly high HUE_{SCY} followed by 10-May. There was significant variation recorded in year analysis, second year (2013) attained higher HUE_{SCY} (4.70 %) than 2012 (Table 2). Thermal energy conversion depends upon genetic capability of plants and growing timing, significantly variation (19 %) was seen among varieties for SCY. Significantly high HUE_{SCY} (1.57 and 1.63 kg ha^{-1} °C days^{-1}) was attained by MNH-886 followed by NIAB-9811 (1.53 and 1.56) while 19 % lower by AA-802 and IR-3701 in 2012 and 2013. Days of the growing season (started 10-March) was regressed with heat use efficiency by developing

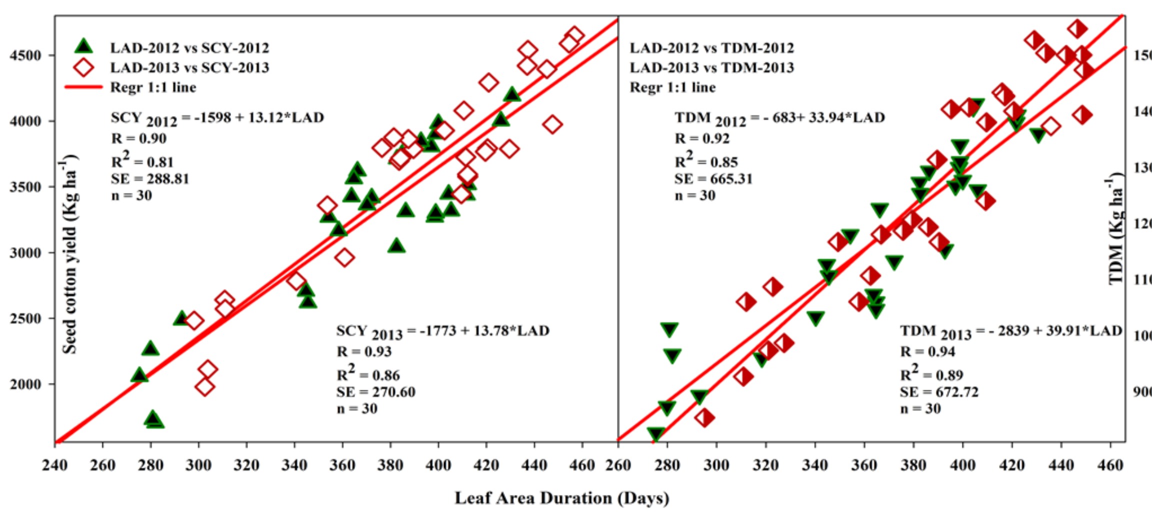

Figure 18. Relationship between leaf area duration with tops weight and seed cotton yield (kg ha^{-1}) of cotton varieties and planting dates for both growing season (2012 and 2013).

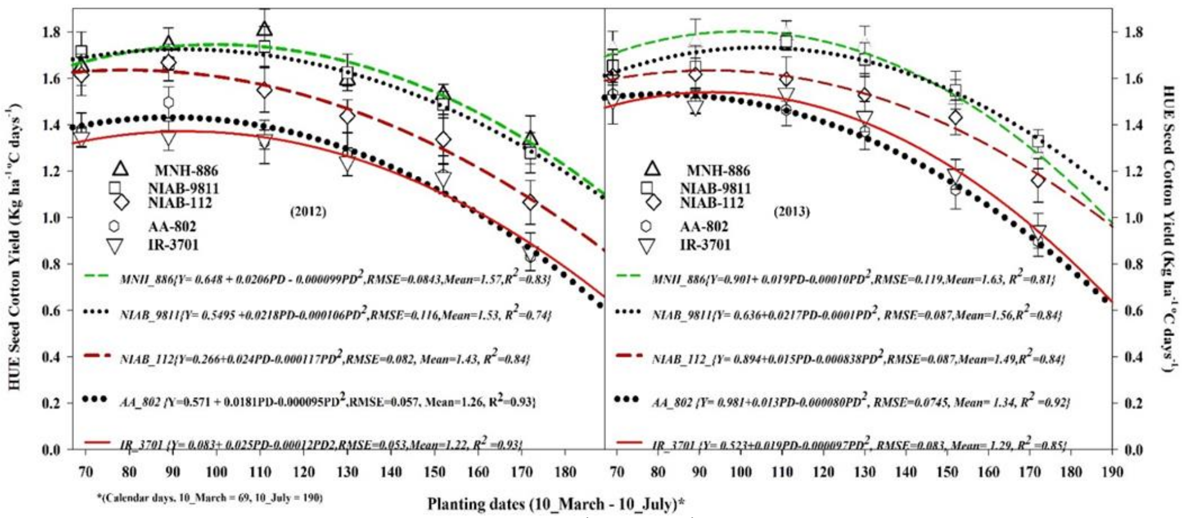

Figure 19. Heat use efficiency-seed cotton yield (kg ha^{-1} °Cdays^{-1}) of cotton varieties at different planting dates (calendar days: 10-March to 10-July) during both growing season (2012 and 2013).

quadratic model for each variety (Fig. 19). Clear decreasing trend was computed for delayed planting from 1-Jnue up to end of the June, varieties almost performed similar here as in case of yield. For year analysis of thermal time and days of the year with HUE_{SCY} for the optimum planting time estimation was regressed using quadratic formula equation. Higher HUE-SCY was attained at early planting window of 89-110 CD and 74-88 CD by AA-802 during 2012 and 2013 respectively than all others while late and longer window was observed for NAIB-9811 (101-111CD, 96-107CD for 2012 and 2013). Cultivar NIAB-112 seemed to be heat tolerant and short duration had planting window of 96-106 CD and 87-100 CD for 2012 and 2013, respectively. Statistical indices seemed good with lowest RMSE (0.05-0.119) and reliable good determination coefficient (0.75-0.93) for both growing years (Fig. 19).

DISCUSSION

Cotton phenology: Planting date had significant effect on key phenological phases of cotton, variation in growing conditions of each planting might lead to big differences in crop growth cycle and phenological phases (Fig. 3, 4 and 5). Negative impacts on changes with too early planting in development were related to delayed emergence, poor and weak cotton stand, longer vegetative phases and decrease in reproductive period. Variation in weather conditions of both years was detected which lead to significant differences in phenological phases, growth and seed cotton yield. More cold shocks (nights <12 °C) and heat stress (days >35 °C) were recorded in 2012 than 2103 growing year, generally mean temperature remained low in early growing sowing in 2012 than 2013 (Fig.1 and 2) so all phenological stages were advanced (early) 0-3 days in 2013 than 2012 for both early and late planting. Early planting experienced cold shock at key phenological phases than optimum planting while late confronted heat stress during developmental stages (Sawan *et al.*, 2002: Bange and Milroy 2004; Luo *et al.*, 2010). But there was no local study to relate the early planting and Bt. and non Bt. cotton varieties phenology, growth and seed cotton yield. Early planting (10-March, 30- March and 21-April) gradually delayed 3-10, 5-13, 3-14 and 2-13 days respectively of first square, flower boll and boll opening respectively than normal planting at 10-May (37, 53, 77 and 103 days). It might be due to poor heat unit accretion in early growing season and clod shock stress which delayed the key phenological events than May planting (Fig. 3, 4 and 5). Plant temperature below or above the thermal kinetic window result in strain that confines growth and delay in phenological phases and ultimately disturb the seed cotton yield (Reddy *et al.*, 2004). Delayed planting (1-June and 21-June) had significant impact particularly on boll development phases due to heat stress, overall phenology and cotton productivity generally by shortening of crop cycle leading to reduction in seed cotton yield and heat use efficiency. Late planting also challenged high temperature at early growth and phenological phases were advanced 4-8, 3-7, 2-4 and 4-6 days respectively (Fig. 3, 4 and 5). Planting on 21-April and 10-May had good crop stand, increased crop vigor due to optimum weather conditions with effective reproductive periods from first square to boll opening. These planting windows avoid early and late cold stress and optimal mean temperature for key phenological phases ultimately promoted growth and seed cotton yield. Six planting dates provide a wider range of weather conditions to evaluate the performance of varieties. Short duration cultivar (NIAB-112) attained 6 to 8 less days for all phenological events than longer duration (AA-802 and IR-3701) varieties during growing seasons. Positive impacts on changes in development of medium duration cultivars (MNH-886 & NIAB-9811) were related to potential increase in the reproductive period as a result of earlier first square and delayed last effective square which ultimately lead to increase in seed cotton yield (Bibi *et al.*, 2003; Kakani *et al.*, 2005; Sing *et al.*, 2007). Decreasing linear trend was regressed between days of the growing seasons with phot thermal days after sowing for each variety for all key phenological stages (Fig. 4 and Fig. 5), as temperature increased it shortened the growth cycle and phenological phases (Sawan *et al.*, 2002; Bang *et al.*, 2008), delayed planting required less time to switch into next phenological event due to high temperature and longer photoperiod hours at later reproductive stages. Moreover 18 days shortened up to boll opening of last planting (21-June) as compared with 10-March planting and boll development process drastically reduced and affected the quality and yield mainly by high temperature at key phenological phases (Reddy *et al.*, 2004; Constable and Bange 2006). In short temperature below thermal kinetic window (TKW) take more days to complete specific phase and less for above TKW although cotton cultivars also differ their growth potential when bear different or same climatic condition (Sing *et al.*, 2007; Arshad *et al.*, 2007b; Luo *et al.*, 2014).

As temperature increased with the passage of spell, thermal time accretion gradually increased and attained peak at 10-May planting then decreased with increasing trend up to end date during growing seasons (Fig. 6-8). Early two and last one planting attained lower thermal time (day degrees) for each key phenological phase, first one due to very low temperature during early growth phases (Bange *et al.*, 2008; Luo *et al.*, 2010) and former due to less days taken to switch another phenophase because it faced high temperature stress (>40 °C) and long photoperiod (Fig. 1 and 2) to complete life cycle (Sawan *et al.*, 2002). Quadratic trend was observed in day degrees accretion, although early planting (10-March and 30-March) required 14 more days for key phenological stages but temperature increasing rate is too high so early planting accumulate less days degree than others. Higher difference (46 and 33 %) for day degrees accretion was computed for early phenological phases (square and flower initiation) while lower (20 and 13 %) for boll initiation and boll opening in comparison of 10-May planting with 1st planting date (Fig. 6-8). Varieties IR-3701 and AA-802 being a longer growth cycle accumulated higher day degrees for all phenological phases when planted at 10-May than short one (NIAB-112) planted on 10-March. Lower accrual of day degrees was reported by Bange and Milroy (2004) at early planting for all key phenophases while higher thermal time for all phenological events was accumulated when cotton was planted during peak season (Sawan *et al.*, 2002; Sing *et al.*, 2007). Yeates *et al.* (2010) reported thermal time requirement of different phenological phases planted at variables dates with cotton cultivars, there are variation between results due to differences in climatic conditions and growing seasons but generally overall results are in range (Bange *et al.*, 2008; Luo *et al.*, 2010) while our findings are in line with the study conducted in semi-arid climatic conditions, thermal time was in range for first square, flower, boll initiation and boll opening (633, 861, 1222, 1616 °C days, respectively) but it was only for April planting (Gudadhe *et. al.*, 2013).

***Cotton growth*:** Initial growth of LAI at early planting (10-March) was very slow due to harsh climatic conditions faced especially cold shock, poor thermal time accretion, lower sunshine hours and solar radiation (Fig. 2), progressively increased attained maximum LAI very late (110-120 DAP) in the season than last planting (80-90 DAP) afterwards decreasing trend was observed in all planting dates (Fig. 9 and 10) but with increasing trend, not sudden decline as in other agricultural crops due to indeterminate in nature (Bange and Milroy, 2004; Wajid *et al.*, 2010; Ali *et al.*, 2014). Generally peak LAI was attained during flowering to boll opening phenological phases with values fluctuated 3.38-4.52 wide-ranging (Table 2) due to variation in weather conditions of planting windows (Sawan *et al.*, 2002). Although these values are higher than previous studied (Ali *et al.*, 2009; Iqbal *et al.*, 2010; Wajid *et al.*, 2014) due to different genetic makeup. There is no locally previous study conducted for too wider planting windows with a range of promising varieties (Bt. and non Bt.) adopted at farmer's field. Increasing trend in peak LAI was observed with delay in planting at 21-April and 10-May than too early planting (10-March) with all varieties while too late planting (1-June and 21-June) had confronted with heat stress (>45 °C) and excessive thermal heat index limited the growth and TDM accretion (Fig. 2, 9-12). Our results are almost in range than previous studies related to nitrogen application (Wajid *et al.*, 2010, 2014), delayed planting with shorter windows (Ali *et al.*, 2009), only with non Bt. cultivars which are no longer being cultivated (Iqbal *et al.*, 2010; Arshad *et al.*, 2007a). Being indeterminate in nature, cotton crop continued to grow new leaves as fast than leaf senescence which ultimately leads to high LAI outside the values that contribute to high CGR. Almost similar trend was observed in CGR time series development with passage of time, attained maximum 90-110 DAP for all varieties when planted on 10-March while 10-May planting achieved early 90 DAP and 1-June and 21-June attained maximum CGR too early up to 70-90 days (Fig. 14 and 15) but variation existed due to differences in genetic and canopy architecture (Reddy *et al.*, 2005; Sing *et al.*, 2007). Discrepancy was found more apparent due to variation in leaves and canopy structure lead to variation in LAI and CGR. Similar results have been noted in previous studies (Iqbal *et al.*, 2010; Ali *et al.*, 2009; Wajid *et al.*, 2010) but limited up to three planting dates and non Bt. cultivars only. Decreasing trend in net assimilation rate (NAR) led to negative effect on further increase of LAI and

CGR resulting in out of phase LAI and CGR curves. Increasing LAI promoted the TDM accretion which leads to decline in CGR (Ali *et al.*, 2009). Increasing trend in LAI support CGR growth in early August after that sudden decrease in NAR execute reduction in crop growth rate and LAI also start decreasing at the end of this month, so reduction in both LAI and NAR after that imposed reduction in CGR at the end of the season.

Early planting (10-March to 21-April) attained significantly higher biomass accumulation than last planting (21-June) during both the growing seasons (Table 2). Reduction in TDM accumulation due to shorter growing cycle in delayed planting (1-June and 21-June) might be due to lower number of fruit and non-fruit branches and plant height as vegetative growth and dry matter portioning to reproductive parts at different phenological phases are sensitive to weather conditions (Yates *et al.*, 2010). Increasing accumulation rate in biomass was upsurge with delay in planting, 1st planting faced sub optimal weather conditions during early vegetative growth than 21-April and 10-May planting while 30-March experienced these conditions for less period of time (Fig. 11-12). Sub optimal weather conditions and heat stress especially faced by late planting (1-June and 21-June), early growth stages lead to variation in biomass accretion, late planting maintained maximum growth rate for shorter duration than early planting (10-March and 30-March) so generally accrued lower biomass (Iqbal *et al.*, 2010; Wajid *et al.*, 2010). Long duration varieties (MNH-886, IR-3701 and AA-802) attained high biomass accretion than short one under both years' climatic conditions. Similar result of biomass accumulation was observed by Wajid *et al.* (2010) for May planting under arid conditions using nitrogen and cultivars as main treatments. Our results are little bit higher than those found under arid to semi-arid climatic conditions with planting dates (May to June) and non Bt. cotton cultivars only (Ali *et al.*, 2009). Variation in biomass accretion was found at different day and night temperature, longer sunshine hours (16 h) and cold shock (>12 °C) promoted vegetative growth while short photo period (12 h) with high night temperature (16 °C) were found better for seed cotton yield (Sawan *et al.*, 2002). Cotton biomass production is strongly related to time during which plant foliage remained within range of thermal kinetic window (23.5-32 °C), biomass productivity therefore directly influenced by TKW and temperature experienced by the plants during season (Sawan *et al.*, 2002). Early planted varieties (89 and 111 CD) attained higher biomass because these planting harvested supra optimal growth conditions (30/22 °C) at vegetative phase, these climatic conditions enhanced number of nodes to the first fruiting branch which ultimately promote the biomass accretion and faced sub optimal at reproductive phases (40/32 °C) which affect reproductive structure, excessive fruit loss ultimately resulted less seed cotton yield (Reddy *et al.*, 2004; Yeates *et al.*, 2010). In late sown due to shorter time for vegetative growth and lower biomass accretion which unable to support high fruit load, in this condition crop may be moved more quickly to "cutout" and result in the seed cotton reduction (Bange and Milroy, 2004).

Seed cotton yield (kg ha^{-1}) and heat use efficiency (kg ha^{-1} °C days^{-1}): The highest seed cotton yield was produced at 30-March to 10 May planting by varieties MNH-886 and NIAB-9811 (NIAB-Kiran) using resource efficiently and maturity (final picking) was occurred in end of October before the growing season of wheat crop (Table 2, Fig. 16 and 17). While too early planting (10-March) influenced by sub optimal weather conditions (cold stress, lower photo thermal days, sun shine hours and solar radiation) at early and reproductive phases (>35 °C, longer photo period) because these phenological phases (flowering and boll development) confronted with heat stress, fruit shedding and abortion may lead to reduction in seed cotton yield but it is still high than delay planting (1-June and 21-June) due to longer growing seasons and better vegetative growth (Fig. 16 and 17). Delayed planting lose seed cotton yield in all varieties due to short growing season, less biomass accretion and high temperature stress at early reproductive phases while cold temperature, lower photo period and solar radiation at boll development phases are major contributor to lower production (Fig. 2, 16 and 17). It is evident from literature that delayed planting had significant reduction in seed cotton yield (Iqbal *et al.*, 2010; Arshad *et al.*, 2007b; Ali *et al.*, 2009; Wajid *et al.*, 2010), these results are found high due to difference in genetic potential of cultivars and variation in weather conditions, actually these studies were conducted under arid environment but no indigenous study was found for so longer planting windows for promising Bt. and non Bt. cotton varieties for adoption at farmers field. It is clearly evident from results that too early planting (10-March) had experienced sub optimal weather conditions at early growth and later reproductive phases which impact the biomass portioning, source sink relationship and unable to meet the boll demand due to reduction in boll filling period ultimately less seed cotton yield produced than April and May planting (Bange and Milroy, 2004; Yeates *et al.*, 2010; Luo *et al.*, 2014). Although, early planting had longer season, crop growth can be maintained and fruit loss can be remunerated by the new plant growth but longer season duration tied with higher temperature which required more resources as irrigation and fertilizer to attain same or more seed cotton yield (Constable and Bange, 2006; Yeates *et al.*, 2010).

Significantly higher heat use efficiency (1.55 to 1.59 kg ha^{-1} °C days^{-1}) was computed for 10-March to 21-April planting while lowest for 21-June planting. Varieties (MNH-886 and NIAB-9811) used heat more efficiently followed by NIAB-112 when planted 10-March to 21-April planting window than others (Table 2) because optimum planted cotton attained higher seed cotton yield by using heat unit accretion efficiently, actually temperature and solar radiation were found super optimum during growing conditions (Fig. 2 and 19) which enhanced favorable physiological activities as well that assure higher seed cotton yield (Sawan *et al.,* 2002*;* Reddy *et al.,* 2005). Least heat use efficiency (1.09 kg ha^{-1} °C $days^{-1}$) was computed in 21-June planting, it emphasized that delayed planting cotton could not utilize the sources efficiently especially solar radiation, photoperiod and temperature. The main reason behind this study is variation in temperature and solar radiation at different growing stages in different planting windows (Wilson *et al.,* 2003; Constable and Bange, 2006). Lower heat use efficiency in delayed planting might be due to poor thermal time accretion and sub optimal bioclimatic indices later in the season and night and day temperature both remained higher during reproductive development leads to detrimental effect on biomass accretion and seed cotton yield (Sawan *et al.,* 2002*;* Sing *et al.,* 2007). Present findings are in confirmation with the results of Gudadhe *et al.* (2013) but our outcomes are high might be due to genetic and environmental variation reduced HUE, ultimately lowered SCY. Maximum seed cotton yield potential among planting dates was observed for April planting which had super optimal weather conditions from planting to harvesting but it has chance of receiving rain which could affect the sowing and germination. To evaluate the probability of April planting at commercial scale, further modeling exploration with combination of historical climatic and future data is prerequisite for climate assessment and its impact on cotton productivity.

***Conclusions*:** In conclusion, cotton varieties MNH-886 and NIAB-9811 (NIAB-Kiran) planted between 30-March to 10-May outperformed with higher seed cotton predominantly due to longer appropriate growing season by utilizing super optimal weather conditions, attained optimum growth at all key phenological phases which lead to higher HUE. Delay in planting (21-June) due to short and sub optimal growing season resulted 40 % seed cotton yield penalty, poor bioclimatic and growth indices, planting during 1-April to 10-May can be recommended for the farmers field to avoid weather stress and efficient utilization of resources for sustainable cotton production in the region. Genotypic variations was assessed by developing thermal, photo thermal, growth and SCY statistical models for different phenological phases and final seed cotton yield on daily basis was estimated for accurate assessment. Varieties MNH-886 and NIAB-9811 (NIAB-Kiran) attained higher thermal, growth, development indices at all phenophases and seed cotton yield by efficiently utilization of weather conditions and available resources while NIAB-112 performed good as short duration variety and it attained high seed cotton yield for late planting (1-June) as well. It seemed heat tolerant hence it can also be recommended for early and especially for late plating in the region. Varieties MNH-886, NIAB-Kiran and NIAB-112 can be adopted at farmer's field in the region for maximizing cotton production under uncertain environment. Further, information regarding estimated parameters using studied models of bioclimatic, growth and yield under different climatic conditions will provide rigorous prediction for management decision optimization, production and efficiently resources utilization.

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